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The impact of aviation fuel tax on fuel consumption and carbon emissions: The case of the US airline industry

Hideki Fukui

Policy Research Office, Aviation Strategy Division, Civil Aviation Bureau

Ministry of Land, Infrastructure, Transport, and Tourism

2-1-3 Kasumigaseki, Chiyoda-ku,

Tokyo, 100-8918 Japan

E-mail: fukui-h2fs@mlit.go.jp; fukui.hideki.mb@gmail.com

Phone: +81-3-5253-8695

Chikage Miyoshi

Centre for Air Transport Management, School of Aerospace, Transport, and Manufacturing, Cranfield University

Martell House, Bedford MK43 0TR, United Kingdom

E-mail: c.miyoshi@cranfield.ac.uk

Phone: +44 (0)1234 754 976

Abstract

We examine the effect of an increase in aviation fuel tax on reductions in fuel consumption and carbon emissions using data from the US airline industry. The results of simultaneous quantile regression using an unbalanced annual panel of US carriers from 1995 to 2013 suggest that the short-run price elasticities of jet fuel consumption, which are negative and statistically significant for all quantiles, vary from -0.350 to -0.166. The long-run price elasticities show a similar pattern and vary from -0.346 to -

0.166. However, they are statistically significant only for the 0.1, 0.2, 0.3, and 0.5 quantiles. The results suggest that the amount of the reduction of fuel consumption and CO_2 emissions would be smaller in the longer term. Our calculation, using values from 2012, suggests that an increase in aviation fuel tax of 4.3 cents, which was the highest increase in aviation fuel tax in the US during the analysis period, would reduce CO_2 emissions in the US by approximately 0.14 percent to 0.18 percent in the short run (1 year after the tax increase). However, perhaps due to the rebound effect, the percentage reduction in CO_2 emissions would decrease to about 0.008 percent to 0.01 percent in the long run (3 years after the tax increase).

Keywords: fuel tax; fuel consumption; CO_2 emissions; US airline industry

JEL Codes: H23; R11; R48

1 Background

The aviation sector's contribution to global greenhouse gas (GHG) emissions has been relatively small, with a 2010 share of approximately 2.02 percent of total CO_2 emissions worldwide (calculation based on European Union Global Emissions EDGAR v4.2 FT2010). According to our calculation based on the 2012 data of the US Environmental Protection Agency (EPA), US carriers' domestic flights account for about 2.3 percent of CO_2 emissions in the US. Even if we include international flights, US carriers accounted for only about 3.5 percent of CO_2 emissions in the US in the same year.

However, despite advances in technology, which have improved the fuel efficiency of aircraft significantly over the past 20 years, the amount and proportion of CO_2 emissions from the aviation sector have been increasing steadily in the US. The solid line in Figure 1 shows that the fuel consumption per mile flown by US carriers dropped from approximately 3.7 gallons in January 1990 to around 2.3 gallons in December 2013, which suggests a remarkable improvement in fuel efficiency. Although more frequent flights with smaller aircraft may have contributed to increased fuel consumption per mile flown, increased average stage lengths may have contributed to lower fuel consumption per mile flown. On the other hand, the dotted line in Figure 1 suggests that the total fuel consumption by US carriers has not decreased as dramatically as the fuel consumption per mile flown. This may be because the significant growth in air transport demand in the US, which is shown in Figure 2, has outpaced the fuel efficiency gains. As shown in Figure 3, the annual total CO_2 emissions in the US have decreased since 2007, and those in 2012 (5024.7 $MMTCO_2$) were virtually at the same level of 1995 (5041.2 $MMTCO_2$). In contrast, as Figure 4 shows, the annual CO_2 emissions from commercial flights by US carriers have increased steadily for the past 20 years, and those in 2012 (174.7 $MMTCO_2$) reached around 9.5 percent above the 1995 level (159.6 $MMTCO_2$). Again, this is mainly due to the ever-growing demand for international air travel, which has resulted in significant increases in fuel consumption, offsetting fuel efficiency improvements. Consequently, the proportion of CO_2 emissions from the aviation sector in the US has been rising steadily, as depicted by the bold solid line in Figure 4. The amount of CO_2 emissions from the aviation sector remains small compared to the total amount of CO_2 emissions (approximately 3.5 percent of total emissions in 2012). However, in light of the strong demand for international air travel and the expected increase in demand, CO_2 emissions from the aviation sector are likely to increase rapidly without concerted efforts by policymakers and the industry to reduce emissions (see Mayor and Tol, 2010; Owen et al., 2010; Preston et al., 2012).

[Figure 1: Fuel consumption per mile flown by US carriers]

[Figure 2: Monthly total miles flown by US carriers]

[Figure 3: Annual total CO_2 emissions in the US]

[Figure 4: Annual CO_2 emissions from commercial flights in the US]

For the past decade, the International Civil Aviation Organization (ICAO) and its member states have been working with the aviation industry to address CO_2 emissions from international aviation by developing a global scheme for this sector. However, the aviation sector has not yet been fully subject to any greenhouse gas (GHG) regulations, perhaps only except for those of the European Union (EU). The EU launched its

Emissions Trading System (EU ETS) in 2005. Since the beginning of 2012, the system has covered the CO_2 emissions produced by aviation activity, including all flights within the EU and between countries participating in the EU ETS (European Commission (EC), 2006; EC, 2009). Later, in 2013, EC directives regarding the EU ETS were amended to include aviation activities within the scheme for GHG emission allowance trading by 2020, although the scheme only covers activities within the EU (EU, 2014). The ICAO is expected to establish a global market-based measure (MBM) in 2016.

In terms of reducing the amount of CO_2 emissions, the cap-and-trade system and fuel tax are closely related but are different policy measures. A cap-and-trade system constrains aggregate emissions first by setting the cap on overall emissions levels and creating a monetary value of emissions for trading and then by allocating a limited number of free emission allowances. In contrast, when employing a fuel tax, it is impossible to determine the amount of the reductions in CO_2 emissions in advance. Thus, the concept of a cap-and-trade system is becoming widely accepted as a more appropriate and efficient approach to achieving environmental objectives and targets than a fuel tax.

However, if the market carbon price drops too low, the incentives to reduce emissions will also be reduced. In fact, as of 2014, the EU ETS "faces a challenge in the form of a growing surplus of allowances [of Certified Emission Reductions (CERs) and European Union Allowances (EUA)], largely because of the economic crisis which has depressed emissions more than anticipated" since 2009 (EC, 2014a). According to the EC, the surplus stood at almost two billion in allowances in early 2012 and had grown further to over 2.1 billion by the end of 2013. Moreover, the EC noted that "While the rapid build-up is expected to end from 2014, it is not anticipated that the overall surplus will decline significantly" (EC, 2014b). In the longer term, this could negatively affect the ability of the EU ETS to reduce emissions. A critically important element is the establishment of a market-determined price for EU allowances (Miyoshi, 2014). The EU ETS system designed in 2012 will not produce substantial emission reductions from air transport (Vespermann and Wald, 2011) due to the current low price of carbon in the market. To make the scheme effective, the carbon price needs to be high (Derigs and Illing, 2013; Miyoshi, 2014; Sgouridis et al., 2011; Vespermann and Wald, 2011).

MBMs such as the EU ETS can be cost effective. However, in some particular circumstances, their effects will be limited, and combining them with other economic instruments, such as fuel tax, can create compatible mechanisms (Carlsson and Hammer, 2002; Mayor and Tol, 2007). In light of these circumstances, and especially considering the growing contribution of the aviation sector to global GHG emissions and the recent challenges of the EU ETS to control an effective carbon price, it is worthwhile to examine the effect of an increase in fuel tax on reductions in fuel consumption and CO_2 emissions. Even though a fuel tax cannot control the amount of CO_2 emissions, it could be an important complementary tool in a CO_2 emissions reduction policy. Therefore, this paper aims to estimate how effective fuel tax could be as a tool to abate emissions from aviation activity, both domestic and international, by using historical data from the US for the period of 1995 to 2013.

The rest of this paper is organized as follows. Section 2 reviews previous studies. The methodologies, models, and data are explained in Section 3. The results are presented and discussed in Section 4. The effects of an increase in aviation fuel tax on reductions in fuel consumption and CO_2 emissions are estimated in Section 5, and Section 6 concludes.

2 Previous studies

The role of the air transport industry has been widely discussed with regard to its efforts to reduce GHG emissions and contribute to addressing the climate change challenge. Among the important measures discussed are the economic instruments for reducing CO_2 emissions, such as ETSs. The advantage of an ETS is that the regulator can set a clear target for emissions reductions by fixing the overall emissions levels. In addition, the tradable permit scheme increases the polluters' choices for reducing their emissions and at the same time lowers the total abatement cost for achieving the target (Ison et al., 2002; Mendes and Santos, 2008). Carriers can use various means, such as technological investment, production reduction (cutting capacity), moving routes, or the purchase of permits (low-cost abatement carriers can sell to high-cost abatement carriers). In addition, tradable permits do not suffer from inflation, as they are traded at market price. In contrast, inflation reduces the real value of the tax. Thus, tradable permits can be more cost effective compared to a tax-based emissions reduction system.

However, there are several issues with tradable permits. First, the initial allocation is very important for the emitters (air carriers), as it uses the market share during the monitoring year to set the allocation rate based on the benchmark established. As a result, the total amount of emissions in the monitoring year increases. This is a very contradictory outcome, although it often happens in other sectors (Miyoshi, 2014). It may result, for example, from the practice of some low-cost carriers (LCCs) carrying freight and mail in their holds during the monitoring year to increase their allocation.

Second, tradable permits become a barrier to entry, which creates anticompetitive issues for new entrants in the market. In addition, the monitoring and implementation costs become a burden for carriers, as they represent additional costs, especially for small-sized carriers.

The most crucial issue is the carbon price. This fell to 2.66 euros per metric ton on April 23, 2013. The current carbon market price is recovering but is still considerably lower (around 7 euros in November 2014) than expected (European Carbon Index (ECarbix)). If carbon prices remain low, emitters (air carriers) prefer to purchase carbon allowances over investing to reduce emissions. Sgouridis et al. (2011) estimated the impact of the carbon pricing scheme on carbon reduction, focusing on two scenarios: the real price of a metric ton of CO_2 being 50 US dollars (in 2005 constant dollars) and 200 US dollars, equivalent to an increase in the kerosene price in the range of 0.5 to 2 US dollars per gallon. The impact on both demand and emissions is minimal in the case of 50 US dollars per ton of CO_2 but becomes a significant reduction in the case of 200 US dollars per ton. Therefore, the carbon price should be high to be more effective in reducing CO_2 emissions. Other researchers, e.g., Vespermann and Wald (2011), also suggest that a more restrictive ETS design is necessary to reduce CO_2 emissions more effectively. If the carbon price remains low, it is appropriate and desirable to develop and apply alternative complementary instruments, such as a fuel tax, in implementing CO_2 emissions reduction policies.

Strictly speaking, fuel tax and ETSs are different (Ison et al., 2002). In fact, fuel tax was not originally designed for environmental purposes.[1] However, it can help reduce

[1] Although systematic aviation fuel tax data are hard to obtain, Keen and Strand (2007) point out that several countries, such as the US and Japan, impose an aviation fuel tax on commercial air carriers. In Japan, the aviation fuel tax system has been established as a financial resource to develop and

fuel consumption and CO_2 emissions (Sterner, 2007). For example, Hofer et al. (2010) investigated how taxing air travel emissions can affect carbon emission levels across multiple transport modes, using data from the US domestic market. They assumed an emissions-tax-driven fare increase of 2 percent and an own-price elasticity of -1.15. Their analysis shows that these assumptions result in an estimated demand decrease of approximately 2.3 percent and a decrease in carbon emissions of over 2.5 million tons (5.5 billion pounds) (2004 data). (However, around one third of the savings in air travel carbon emissions could be offset by the rise in vehicle emissions.) As Hofer et al. (2010) note, fuel tax can be a supplementary tool in combination with an ETS, making up for the deficiencies of both instruments (fuel tax and the ETS) specific to global MBM implementation.

There are several studies on the impact of aviation fuel tax on fuel consumption and GHG emission reductions, which include Pearce and Pearce (2000), Olsthoorn (2001), Mayor and Tol (2007), and Tol (2007). However, Pearce and Pearce (2000), Mayor and Tol (2007), and Tol (2007) do not estimate the price elasticity of jet fuel consumption. Indeed, Pearce and Pearce (2000) estimate the monetary value of the environmental externalities associated with aircraft movements and hence damage-based environmental taxes for aircraft. Mayor and Tol (2007) and Tol (2007) estimate the impact of a carbon tax on aviation fuel, but their studies are based on the simulation

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manage airports. A thirteenth of the total revenue of fuel tax has been allocated to the Airport Development Special Account since 1972 (Airport Development Special Account Act, Supplemental Provision 11). The rest goes to the Treasury. In the case of the US, the revenues from the international arrival/departure tax, federal aviation fuel tax, and other taxes go to the General Fund and are then transferred to the Airport and Airway Trust Fund, which covers all Federal Aviation Administration (FAA) airport facilities, equipment, development, and support for over 75 percent of the FAA's operation and management (Button, 2005). Hence, those aviation fuel taxes have been introduced and used for developing, operating, and managing airports as one of the main financial resources.

model of international tourist flows. Olsthoorn (2001) estimates the price elasticity of world jet fuel consumption in international commercial aviation. Unfortunately, the price data used in Olsthoorn (2001) is not jet fuel price but crude oil price. While crude oil and jet fuel prices have tended to follow a similar pattern, they are not the same thing. In sum, to the best of our knowledge, there are few empirical studies of elasticity of jet fuel consumption with respect to jet fuel price. Our contribution, therefore, is to estimate the price elasticity of jet fuel consumption by using US historical data of jet fuel price and consumption for domestic and international flights, which would reveal the impact of aviation fuel tax on fuel consumption and how effective fuel tax can be as a tool to abate emissions from the aviation industry.

3 Model and data[2]

Our basic estimation model has the following specification, commonly used in previous studies (Burke and Nishitateno, 2013; Davis and Kilian, 2011; Haughton and Sarkar, 1996; Hughes et al., 2008; Kim et al., 2011; Lin and Prince, 2013; Zou et al., 2014):

$$\log(y_{it}) = \alpha + \gamma \log(p_{it-1}) + x_t\rho + \delta_t + c_i + u_{it} \tag{1}$$

The subscripts i and t represent carrier and year. The dependent variable, y_{it}, is each US carrier's annual jet fuel consumption in gallons (domestic and international), and p_{it-1} is the annual average inflation-adjusted after-tax price of jet fuel per gallon (domestic and international) paid by each US carrier in the previous year (Unit: USD). We use

[2] Details of data sources are described in Appendix A.

aggregated data of domestic and international flights. However, the aviation fuel tax in the US applies only to domestic flights (US IRS, 1999). Thus, the tax is added only to the price of jet fuel used for domestic flights. As we use a log-log functional form, the coefficient of interest, γ, shows the price elasticity of jet fuel consumption. The data are taken from the US Department of Transportation (DOT), Form 41 Financial Data, Schedule P-12(a). The aviation fuel tax data are drawn from US Internal Revenue Service Publication 510, as shown in Table 1.

[Table 1: Tax rates on aviation fuel in the US since 1994]

The controls, x_t, include the following variables: the September 11 attacks dummy (equals 1 for 2001 and 2002, 0 otherwise); the annual average national unemployment rate (seasonally adjusted) in the US (Source: US Department of Labor (DOL), Labor Force Statistics from the Current Population Survey); each carrier's annual total miles flown on domestic and international flights (DOT Form 41 Traffic Data, T-100 Domestic/International Segment (All Carriers)); and the annual industry average miles flown per gallon, which is calculated using flight data from DOT Form 41 Traffic Data, T-100 Domestic/International Segment (All Carriers) and monthly fuel consumption data from DOT Form 41 Financial Data, Schedule P-12(a).

The September 11 attacks caused extensive flight disruption. In a sluggish economy with high unemployment, the demand for air travel would decrease. Thus, the expected signs of the coefficients are negative for the September 11 attacks dummy and the annual unemployment rate variable.

The total miles flown variable represents each carrier's total annual miles flown (domestic and international). A carrier's fuel consumption increases as its total miles flown increases. Thus, this variable is expected to have a positive sign. The annual industry average miles flown per gallon is included to control for the effects of economies of scale and technological advances. As is clearly shown in Figure 1, the advances in fuel efficiency during the past 20 years have been impressive. The improved fuel efficiency enabled carriers to reduce fuel consumption per mile by about 38 percent in December 2013 compared to January 1990. Long-haul flights are generally more fuel efficient because aircraft usually consume more fuel during takeoff than during cruise flight. Therefore, the fuel consumption per mile could decrease if carriers increase the number of long-haul flights. Put differently, the economies of scale achieved by large-scale operations would contribute to the reduction of the fuel consumption per mile. At the same time, it is the progress in technology itself that has made it possible for aircraft to fly longer distances. This means it is very important to take into account the effects of the improved fuel efficiency brought about by the economies of scale and the advances in aircraft technology when we estimate the price elasticities of jet fuel consumption. The expected sign of this variable is negative.

The aggregate time effects, δ_t, control for annual variations that are common across carriers (captured by year dummies). The fixed effect, c_i, captures all unobserved, time-constant factors (unobserved time-invariant characteristics of carriers) that affect y_{it}. The error, u_{it}, is a time-varying error, i.e., an idiosyncratic error, which represents unobserved factors that change over time and affect y_{it}.

The main explanatory variable, i.e., the annual average inflation-adjusted after-tax price of jet fuel (per gallon) paid by each carrier, is highly likely to be correlated with time-constant carrier characteristics, c_i. As the DOT explains on its website, jet fuel prices reported to the DOT differ from producer prices (DOT, 2013). Reports to the DOT give the cost per gallon of fuel used by a carrier during the month, rather than the price charged by a producer on a single day. Thus, the jet fuel price (p_{it}) reflects the contractual and storage advantages and disadvantages of each carrier, which are not expected to change in the short term. This suggests that the jet fuel price, p_{it}, is correlated with time-constant carrier characteristics, c_i. Pooled ordinary least squares (OLS) regression is biased and inconsistent if p_{it} and c_i are correlated. Therefore, we include carrier dummies in Eq. (1) to control for the carrier fixed effects, c_i.

The inclusion of carrier dummies, however, does not address the issue of price endogeneity caused by the reverse causality: an increase in fuel consumption could lead to an increase in fuel price. To avoid the endogeneity problem, we use a lagged fuel price variable, p_{it-1}, as a predetermined variable. We also lag p_{it-1} twice to estimate the long-run price elasticity of fuel consumption, as shown in Eq. (2). We assume that the error, u_{it}, is uncorrelated with all past endogenous variables.

$$\log(y_{it}) = \alpha + \gamma_1 \log(p_{it-1}) + \gamma_2 \log(p_{it-2}) + \gamma_3 \log(p_{it-3}) + x_t\rho + \delta_t + c_i + u_{it} \tag{2}$$

An additional advantage of using the lagged fuel price variables is that it makes the analysis more realistic. In the short term, e.g., one to several months following the fuel price changes, carriers' schedules and equipment are relatively fixed. Thus, it is usually difficult for carriers to change their schedules, route structures, and operating practices immediately after the fuel price increases. Besides, investment in new equipment and technology extends over several years before the investment results in fuel savings. In this sense, using the lagged fuel price variables is more realistic than using the fuel price variable in the current year, which postulates a change in fuel price has an immediate and contemporaneous effect on fuel consumption.

4 Estimation results

4.1 OLS estimates from the static and distributed lag models

Table 2 presents descriptive statistics for the unbalanced annual panel of 114 carriers for the period of 1995 to 2013 (See Appendix B for the list of air carriers that appear in our data set). Table 3 reports the results, estimating Eqs. (1) and (2) by means of the pooled OLS: columns 1 and 2 show the estimation results from the static model; columns 3 and 4 present the results from the distributed lag model. Columns 1 and 3 report the estimates with year fixed effects, whereas columns 2 and 4 indicate the estimates without year fixed effects but controlling specifically for income effects. Columns 1 to 4 show the expected negative coefficient estimates for the lagged jet fuel price, p_{it-1}. Additionally, the estimates for p_{it-1} from the static model shown in columns 1 and 2 are statistically significant.

[Table 2: Descriptive statistics]

[Table 3: Estimation results from OLS]

The estimation results from the static model with year fixed effects (column 1 of Table 3) show that the short-run price elasticity of jet fuel consumption is -0.431. However, the coefficients of all the control variables except for the annual total miles flown variable do not have the expected signs. Although none of the coefficients with wrong signs is statistically significant, the results suggest that the model is not properly specified. Hence, we include the US annual average of monthly per capita personal income in Eq. (1) instead of the year fixed effects. We tried to include both effects in the model, but it was impossible due to multicollinearity. Column 2 of Table 3 reports the results. The coefficient of p_{it-1} decreased to -0.414, though it is still statistically significant. In addition, the coefficients of all the control variables show the expected signs, and the coefficients of the total miles flown variable and the income variable are statistically significant. Thus, we consider the model shown in column 2 to be more appropriate for our data set. The results suggest that the short-run price elasticity of jet fuel consumption is 0.414, i.e., a one-percent increase of jet fuel price leads to about a 0.414-percent decrease of jet fuel consumption.

Columns 3 and 4 of Table 3 report the results from the distributed lag model, which is intended to estimate the long-run price elasticity of fuel consumption. Again, the results from the model with year fixed effects, which are reported in column 3, show that the coefficients of all the control variables except for the annual total miles flown variable do not have the expected negative signs. In contrast, as shown in column 4, the coefficients of all the control variables show the expected signs when we include the income variable instead of the year fixed effects. Therefore, here also, we consider the latter model shown in column 4 to be more appropriate than the former model shown in column 3.

The estimated long-run price elasticity of fuel consumption in column 4 of Table 3 is -0.329 (≒ -0.247 – 0.0343 – 0.0472). If the elasticity is statistically significant, it means that jet fuel consumption decreases by about 0.3 percent after 3 years, given a permanent one-percent increase in fuel price. However, none of the coefficients of p_{it-1}

through p_{it-3} in column 4 is statistically significant. The multicollinearity between the lagged variables may make it difficult to estimate the effect at each lag. To obtain the standard error of the estimated long-run price elasticity, we let $\beta_0 = \gamma_1 + \gamma_2 + \gamma_3$ denote the long-run price elasticity and write γ_1 in terms of β_0, γ_2, and γ_3 as $\gamma_1 = \beta_0 - \gamma_2 - \gamma_3$. Using this to substitute for γ_1 in Eq. (2), we obtain

$$\begin{aligned}\log(y_{it}) &= \alpha + (\beta_0 - \gamma_2 - \gamma_3)\log(p_{it-1}) + \gamma_2 \log(p_{it-2}) + \gamma_3 \log(p_{it-3}) + x_t\rho + \delta_t + c_i + u_{it} \\ &= \alpha + \beta_0 \log(p_{it-1}) + \gamma_2 \log(p_{it-2} - p_{it-1}) + \gamma_3 \log(p_{it-3} - p_{it-1}) + x_t\rho + \delta_t + c_i + u_{it} \quad (3)\end{aligned}$$

The coefficient and associated standard error on p_{it-1}, which are what we need, are shown in Table 4. The estimate is not statistically significant. There are two possible explanations for the result. The first is that the price elasticity of jet fuel consumption is considerably different across carriers, and thus the OLS, which show the average relationship between variables, may indicate only a limited aspect of the effect of price on jet fuel consumption. The second is that the presence of a positive rebound effect offsets the reduction in jet fuel consumption in the long run. The first and second possibilities are examined in subsections 4.2 and 4.3, respectively.

[Table 4: Long-run price elasticity of fuel consumption estimated by OLS]

4.2 Quantile regression estimates from the static model

The OLS regression measures the average relationship between jet fuel consumption and movements in fuel prices. This may provide only a partial view of the relationship. Indeed, jet fuel consumption is marked by continuous distribution and changes that may not be revealed by an examination of averages. For example, lower consumption quantiles would contain a large number of smaller carriers, while upper consumption quantiles contain a large number of larger carriers. Smaller carriers may be more vulnerable than larger carriers to the fuel price increases because smaller carriers' financial resources are usually limited compared to larger carriers. In contrast, it is often assumed that larger carriers enjoy some cost advantages over smaller carriers due to their large-volume and long-term fuel purchasing contracts or fuel hedging strategy or both. Fuel hedging means "locking in the cost of future fuel purchases" (Morrel and Swan, 2006) via a commodity swap or option. Although fuel hedging prevents air carriers from gaining from a sudden drop of fuel price, it protects them against losses from a sudden rise of fuel price. Thus, this contractual tool makes it possible for air carriers to stabilize their fuel costs (Berghöfer and Lucey, 2014; Lim and Hong, 2014). These advantages may help larger carriers mitigate the impact of jet fuel price increases and result in a smaller price elasticity of jet fuel consumption for larger carriers.

The effect of aviation fuel tax on jet fuel consumption may vary when the price elasticity of jet fuel consumption differs across the quantiles of fuel consumption. Consequently, the estimation results from the OLS regression (Tables 3 and 4), which show the average relationship between jet fuel consumption and movements in fuel prices, may indicate only a limited aspect of the effect of fuel price increase on jet fuel consumption.

To examine the above possibilities and obtain a more complete picture, we reestimate Eqs. (2) and (3) using simultaneous quantile regression. This method is used because it enables examination of the impact of a covariate on either the full distribution or a particular percentile of the distribution, as opposed to just the conditional mean

(Angrist and Pischke, 2009; Cameron and Trivedi, 2010). In other words, the quantile regression method provides information concerning the relationship between jet fuel consumption and jet fuel price at different points in the conditional distribution of the jet fuel consumption.

Columns 1 to 9 in panel A of Table 5 report fuel price coefficients from the model with year fixed effects. Rogers (1992) reports that "[although] the standard errors obtained [for the quantile regression estimates] using a method suggested by Koenker and Bassett (1982) ... appear adequate in the case of homoscedastic errors, they are probably understated if the errors are heteroscedastic" (see also Rogers (1993)). In our models, the Breusch-Pagan/Cook-Weisberg test for heteroskedasticity rejects the null hypothesis of homoskedasticity. Thus, we obtain estimates of the standard errors by using bootstrap resampling of 1000 replications. All the coefficients of p_{it-1} are negative and statistically significant except for the 0.8 and 0.9 quantiles. However, again, the coefficients of all the control variables do not show the expected negative signs except for the annual total miles flown variable. Indeed, the coefficients of the September 11 attacks dummy have positive signs for the 0.1, 0.3, 0.7, and 0.8 quantiles. The coefficients of the average miles flown per gallon variable also have positive signs for the 0.1, 0.7, and 0.8 quantiles. On top of that, all the coefficients of the unemployment rate variable have positive signs except for the 0.9 quantile. Most of the coefficients with wrong signs are not statistically significant. But here again the results suggest that the model is not properly specified. Hence, we include the US annual average of monthly per capita personal income in Eq. (2) instead of the year fixed effects.

[Table 5: Estimation results from simultaneous quantile regression (static model)]

Panel B of Table 5 reports the results. In this model, all the coefficients of p_{it-1} are negative and statistically significant. The coefficient estimates of p_{it-1} for each quantile generally decreased compared to the estimates reported in panel A of Table 5. Regarding the control variables, the coefficients of the September 11 attacks dummy and the average miles flown per gallon variable still have wrong signs for the 0.1, 0.8, and 0.9 quantiles. However, the coefficients of the unemployment rate variable have the expected negative signs for all the quantiles, though none of them is statistically significant. In addition, the coefficients of the income variable have the expected positive signs and are statistically significant for all the quantiles. Thus, we consider the model shown in panel B of Table 5 to be more appropriate for our data set.

The results apparently suggest that the jet fuel price generally has a greater impact at the lower quantiles than at the upper quantiles of jet fuel consumption. However, the Wald test does not reject the null hypothesis of coefficient equality, which suggests the coefficients of p_{it-1} are the same for all the quantiles. In other words, although the estimated short-run price elasticities of jet fuel consumption appear to differ across the quantiles, they are not significantly different in a statistical sense. Nevertheless, the above results are important because the estimates from the quantile regression suggest that the OLS estimates of the short-run price elasticities are negatively biased to some extent. Indeed, the OLS coefficient of p_{it-1} (-0.414) differs considerably from the quantile regression coefficients, even that for the 0.1 quantile (-0.350). Moreover, a different pattern may be observed for the long-run price elasticities, which will be estimated in the next subsection.

Regarding the control variables, the September 11 attacks dummy has negative coefficients for all the quantiles except for the 0.1, 0.8, and 0.9 quantiles. However, none of the coefficients is statistically significant. The September 11 attacks dummy equals 1 for 2001 and 2002 and 0 otherwise. Thus, the effects of the September 11 attacks may have been largely absorbed by year fixed effects. The coefficients of the unemployment rate variable have the expected negative signs, though none is statistically significant. In contrast, the income variable has the expected positive and statistically significant coefficients for all the quantiles. All coefficients of the total miles flown variable have the expected positive signs. They are also statistically significant except for the 0.8 and 0.9 quantiles. None of the coefficients of the annual industry average miles flown per gallon is statistically significant. Besides, the sign of the coefficients is positive for the 0.1, 0.8, and 0.9 quantiles. This may be caused by the rebound effect: improved fuel efficiency provides an incentive to use more fuel. This possibility will also be examined in the next subsection.

4.3 Quantile regression estimates from the distributed lag model

In this section, we examine whether the rebound effect is higher for larger carriers by estimating the long-run price elasticity of jet fuel consumption at different points in the conditional distribution of the jet fuel consumption. The rebound effect in fuel consumption may be higher for larger carriers. Indeed, carriers belonging to the upper consumption quantiles generally serve more routes and offer higher flight frequency than carriers belonging to the middle and lower quantiles. If the rebound effect is amplified by the larger route networks and higher flight frequency, it would provide larger carriers a stronger incentive to consume more fuel. Thus, the long-run price elasticity of jet fuel consumption would be greater for smaller carriers than for larger carriers.

[Table 6: Estimation results from simultaneous quantile regression (distributed lag model)]

Panel A of Table 6 reports the estimates from the distributed lag model with year fixed effects using simultaneous quantile regression. The results show that none of the fuel cost per gallon variables (t-1, t-2, and t-3) is statistically significant. Moreover, more than half of the coefficients of the September 11 attacks dummy, the average miles flown variable, and the unemployment rate variable do not have the expected negative signs. In contrast, panel B of Table 6 shows that when we include the income variable instead of the year fixed effects, all the coefficients of the fuel cost per gallon variable (t-1) are statistically significant except for the 0.1 and 0.5 quantiles. Also, more than half of the coefficients of the above-mentioned control variables have the expected negative signs. Besides, the coefficient of the unemployment rate variable for the 0.9 quantile is statistically significant. Hence, here again, we consider the latter model shown in panel B to be more appropriate than the former model shown in panel A.

The estimated long-run price elasticity of fuel consumption in column 1 of Table 7 is, for example, -0.346 ($\fallingdotseq$ -0.186 – 0.151 – 0.00876) for the 0.1 quantile. To obtain the standard errors of the estimated long-run price elasticities based on the results shown in panel B of Table 6, we employed the same substitution trick used in section 4.2 and estimated Eq. (3) by simultaneous quantile regression. The long-run price elasticities and associated standard errors for each quantile are shown in Table 7. All the coefficients have the expected negative signs. But again, the Wald test does not reject the null hypothesis of coefficient equality. Thus, the estimated long-run price elasticities of jet fuel consumption, which appear to differ across the quantiles, are not significantly different in a statistical sense. However, it is important to note that Table 7 suggests that the long-run price elasticities for each quantile are consistently smaller than the short-run price elasticities (see Table 5). More important is that the long-run price elasticities are statistically significant only for the 0.1, 0.2, 0.3, and 0.5 quantiles. This means that the price elasticities, which are statistically significant for all quantiles in the short run, decrease over time and become zero for other quantiles (0.4 and 0.6 through 0.9). The results suggest that the presence of a positive rebound effect may offset the reduction in jet fuel consumption in the long run. The estimates shown in Table 7 further suggest that the rebound effect in jet fuel consumption may be higher for larger carriers. Indeed, none of the price elasticities is statistically significant for the 0.6 quantile or above. In general, larger carriers enjoy advantages due to their large-volume fuel procurement contracts or hedging strategy or both (Berghöfer and Lucey, 2014; Lim and Hong, 2014). The relative advantage of larger carriers in terms of fuel cost may make it possible for them to minimize the effect of an increase in fuel price in the long run. Moreover, carriers belonging to the upper consumption quantiles generally serve more routes and offer higher flight frequency than carriers belonging to the middle and lower quantiles. Therefore, the rebound effect may be amplified for larger carriers by their larger route networks and higher flight frequency.

[Table 7: Long-run price elasticity of fuel consumption estimated by simultaneous quantile regression]

We regard the results shown in panel B of Table 5 and Table 7 as the most credible estimates for the short-run and long-run price elasticities of jet fuel consumption. The results can be summarized as follows: (1) the short-run price elasticities are negative and statistically significant for all quantiles and vary from -0.350 (0.1 quantile) to -0.166 (0.9 quantile), though they are not significantly different in a statistical sense; (2) the long-run price elasticities are negative and statistically significant only for the 0.1, 0.2, 0.3, and 0.5 quantiles and vary from -0.346 (0.1 quantile) to -0.166 (0.5 quantile) , though, again, they are not significantly different in a statistical sense; (3) the presence of a positive rebound effect may offset the reduction in jet fuel consumption in the long run; and (4) the rebound effect may be higher for larger carriers. Thus, taken together, the results suggest that an increase in fuel prices due to fuel taxation could have a larger impact on smaller carriers than on larger carriers with regard to fuel consumption.

5 Calculation of the effect of an increase in aviation fuel tax on reductions in fuel consumption and CO_2 emissions

Based on the estimated price elasticities, we estimate the aviation fuel consumption effect resulting from a 10-cent aviation fuel tax increase (estimated elasticity × percentage change in the after-tax aviation fuel price in a given year due to a 10-cent increase in aviation fuel tax [10-cent increase in aviation fuel tax / after-tax aviation fuel price in a given year] × 100). We then estimate the reduction in fuel consumption based on the aviation fuel consumption effect. The International Air Transport Association (IATA), the Intergovernmental Panel on Climate Change (IPCC), and the US EPA propose slightly different default emission factors for jet fuel (see Table 8). Thus, we used three different emission factors to calculate the reduction in CO_2 emissions.

Panel A of Table 8 shows the results of the calculation based on the scenario of a 10-cent increase in aviation fuel tax, for which we used the values of fuel price and CO_2 emissions from 2012. The results suggest that, in total, an increase in aviation fuel tax of 10 cents leads to reductions in annual aviation fuel consumption and CO_2 emissions in the US by about 1624 million gallons and 15.8 to 19.4 million metric tons, respectively. A 10-cent aviation fuel tax increase reduces annual CO_2 emissions in the US by approximately 0.33 percent to 0.41 percent. However, the highest increase in aviation fuel tax during the period of analysis was 4.3 cents. Hence, we also calculate the effect of a 4.3-cent aviation fuel tax increase on fuel consumption and CO_2 emissions. The results are not particularly impressive. As shown in Panel B of Table 8, based on this scenario, the reductions in annual jet fuel consumption and CO_2 emissions in the US fall to approximately 698 million gallons and 6.8 to 8.3 million metric tons, respectively. A 4.3-cent aviation fuel tax increase reduces CO_2 emissions in the US by approximately 0.14 percent to 0.18 percent.

[Table 8: Short-run effect of aviation fuel tax on fuel consumption and CO_2 emissions]

In the long run, the impact of an increase in aviation fuel tax on fuel consumption and CO_2 emissions could be further reduced due to the presence of a positive rebound effect. Panels A and B of Table 9 indicate the results of the calculation based on the scenarios of a 10-cent and a 4.3-cent increase in aviation fuel tax. In the scenario of a 10-cent increase in aviation fuel tax, the reductions in annual jet fuel consumption and

CO_2 emissions in the US are approximately 93 million gallons and 0.9 to 1.1 million metric tons, respectively. However, in the more realistic scenario of a 4.3-cent increase in aviation fuel tax, the reductions in annual jet fuel consumption and CO_2 emissions in the US decrease to approximately 40 million gallons and 0.4 to 0.5 million metric tons, respectively. After 3 years, a permanent 4.3-cent aviation fuel tax increase contributes to the reduction of CO_2 emissions in the US by only about 0.008 percent to 0.01 percent. Even if air carriers account for only about 3.5 percent of the GHG emissions inventory in the US, the long-run emission reduction effect is rather small: it represents only about a 0.2- to 0.3-percent reduction of CO_2 emissions in the US aviation sector. In any case, the impact of a 4.3-cent increase in aviation fuel tax on fuel consumption and CO_2 emissions seems to be almost negligible in the long run.

[Table 9: Long-run effect of aviation fuel tax on fuel consumption and CO_2 emissions]

An implicit assumption of the above estimation is that the aviation fuel tax would be passed on fully to carriers. However, if the aviation fuel suppliers bear part of the fuel tax burden, the reductions in fuel consumption and CO_2 emissions caused by the fuel tax would fall further. To examine the pass-through rate of aviation fuel tax to aviation fuel price, we regress changes in aviation fuel prices on changes in aviation fuel tax (cf. Davis and Kilian, 2011; Marion and Muehlegger, 2011). The pass-through rate refers to how the burden of a fuel tax is distributed between sellers and buyers of jet fuel. Our estimation model has the following specification.

$$\log(p_{it}) = \theta + \beta\log(tax_t) + x_t\rho + \delta_t + u_{it} \quad (4)$$

The aviation fuel tax in the US applies only to domestic flights; international flights are exempt from the aviation fuel tax (US IRS, 1999). In addition, as Table 1 shows, the tax rate on aviation fuel in the US has not changed since 1998. Therefore, we estimate the pass-through rate of aviation fuel tax to aviation fuel price by using the data for domestic flights during the period between 1995 and 2000, i.e., the 3 years in which tax changes occurred and the next 3 years in which no tax changes occurred.

In Eq. (4), the subscripts i and t represent carrier and year, respectively. The dependent variable, p_{it}, is the annual average inflation-adjusted after-tax price of jet fuel for domestic flights (per gallon) paid by each carrier in US dollars (Source: DOT, Form 41 Financial Data, Schedule P-12(a)). The explanatory variable, tax_t, is the aviation fuel tax (Source: US IRS, Publication 510). The controls, x_t, are as follows: each carrier's annual total miles flown on domestic flights (logged) (t-1); all carriers' annual average miles flown per gallon on domestic routes (logged) (t-1); US annual average national unemployment rate (seasonally adjusted) (percent); and annual average of US monthly per capita personal income (logged). The aggregate time effects, δ_t, are also included in Eq. (4). The error, u_{it}, is a time-varying error.

[Table 10: Effect of a change of aviation fuel tax on the change of jet fuel price]
[Table 11: Estimated average annual pass-through rate (percent) of aviation fuel tax to aviation fuel price]

Table 10 shows the estimated price elasticities with respect to aviation fuel tax, while Table 11 shows the estimated average annual pass-through rate of aviation fuel tax to aviation fuel price. We obtained price elasticities by estimating Eq. (4) using OLS. The price elasticity obtained from the OLS estimate with year fixed effects is 0.0406 (column 1 of Table 10). The price elasticity slightly increases to 0.0466 when we estimate the model by including the annual average of US monthly per capita personal income variable instead of the year fixed effects (column 2 of Table 10). (Here also, we tried to include both effects in the model, but it was impossible due to multicollinearity.)

An increase in aviation fuel price due to a 1 percent fuel tax increase—which can be calculated by multiplying the after-tax aviation fuel price at a given time by the estimated price elasticity (0.0406 or 0.0466)—would be equal to a 1 percent increase in aviation fuel tax multiplied by the pass-through rate of aviation fuel tax to carriers. Thus, calculated using the mean value of the after-tax aviation fuel price in 2000 (0.588 US dollars per gallon) and the value of the aviation fuel tax in 2000 (0.044 US dollars per gallon), the average pass-through rate of aviation fuel tax to carriers in 2000 was approximately 54.3 percent to 62.3 percent (columns 1 and 2 of Table 11). The estimated pass-through rates are less than 100 percent. These results suggest that aviation fuel taxes have not been passed fully to carriers, and thus, our calculation overestimated the amount of reductions in fuel consumption and CO_2 emissions: the actual amount of reductions could be much smaller than the current estimates.

6 Conclusion

We have examined the effect of an aviation fuel tax increase on reductions in fuel consumption and CO_2 emissions, using data from the US airline industry. Our quantile regression estimates from the unbalanced annual panel of US carriers from 1995 to

2013 suggest that (1) the short-run price elasticities vary from -0.350 (0.1 quantile) to -0.166 (0.9 quantile), though they are not significantly different in a statistical sense; (2) the long-run price elasticities vary from -0.346 (0.1 quantile) to -0.166 (0.5 quantile) and are statistically significant only for the 0.1, 0.2, 0.3, and 0.5 quantiles (though, again, they are not significantly different in a statistical sense); (3) the presence of a positive rebound effect may offset the reduction in jet fuel consumption in the long run; and (4) the rebound effect may be higher for larger carriers. The results for the long-run price elasticities suggest that an increase in fuel prices due to fuel tax has a larger impact on smaller carriers than on larger carriers. Due to the low price elasticities and the low proportion of carriers affected by fuel tax with regard to fuel consumption, the expected reduction in CO_2 emissions resulting from a 4.3-cent aviation fuel tax increase, the highest increase in aviation fuel tax in the US during the period of analysis, is also significantly low: when calculated using values from 2012, the short-run reductions in fuel consumption and CO_2 emissions in the US were approximately 698 million gallons and 6.8 to 8.3 million metric tons, respectively. The short-run reduction in CO_2 emissions in the US resulting from a 4.3-cent increase in aviation fuel tax is only around 0.14 percent to 0.18 percent. In the long run, the presence of a positive rebound effect would reduce the impact of an increase in aviation fuel tax on fuel consumption and CO_2 emissions. A 4.3-cent increase in aviation fuel tax would reduce annual jet fuel consumption and CO_2 emissions in the US by approximately 40 million gallons and 0.4 to 0.5 million metric tons, respectively. After 3 years, a permanent 4.3-cent aviation fuel tax increase would contribute to the reduction of CO_2 emissions in the US by only about 0.008 percent to 0.01 percent. The long-run emission reduction effect resulting from a permanent 4.3-cent fuel tax increase is only about a 0.2- to 0.3-percent reduction of CO_2

emissions in the US aviation sector. This means that in the long run, if we are to achieve a 1-percent reduction of CO_2 emissions in the US aviation sector, the aviation fuel tax needs to be about 3 to 5 times higher than the current level. In addition, the pass-through rate of aviation fuel tax to carriers seems to be less than 1: the estimated average pass-through rate was approximately 54.3 percent to 62.3 percent in 2000. This suggests that aviation fuel taxes have not been passed fully to carriers, and thus, the actual amount of reductions could be much smaller than the current estimates. In sum, our estimates based on historical data suggest that the reduction in CO_2 emissions resulting from a (perhaps) politically feasible increase in aviation fuel tax is almost negligible. (Olsthoorn (2001) reached similar conclusions, though the magnitudes of estimated price elasticity of jet fuel consumption and estimated reduction in CO_2 emissions are different from those of our estimations.)

The results of our study indicate grim implications for policymaking using the MBM with regard to the role of aviation fuel tax in reducing CO_2 emissions. Our analysis suggests that fuel tax has certainly contributed to a reduction in CO_2 emissions. However, the scope and size of its impact is fairly limited and small; the effectiveness of fuel tax as a policy tool to control fuel consumption and CO_2 emissions in the aviation sector is neither impressive nor promising.

Another important finding is that the levels of the impact of fuel tax vary depending on the size of carriers: an increase in fuel prices due to fuel tax has a larger impact on smaller carriers than on larger carriers. Put differently, our estimation results suggest that carriers less able to generate revenues bear a disproportionate burden in terms of CO_2 emissions reduction. Even if fuel tax could be an effective policy tool to control fuel consumption and CO_2 emissions in the aviation sector, it could have uneven effects on carriers and intensify underlying inequities among them. Although emissions trading schemes could be an important complementary tool in a CO_2 emissions reduction policy, they also have similar equity issues (Miyoshi, 2014). Indeed, the first multinational emissions trading scheme, the EU ETS, has raised many regulatory issues and objections, including from the Chicago Convention. Although it is a cost-effective measure, the ETS produces “winners and losers” among participants due to the timing of the scheme implemented. For the global ETS mechanism, equity issues among carriers and countries cannot be avoided. A recent study estimates that 92 percent of fuel burning takes place in the Northern Hemisphere, and 67 percent of this occurs between 30° N and 60° N (Simone et al., 2013).

Thus, in developing economic instruments such as fuel tax and an emissions trading system, considering equity is a key element (Button, 2005; Eliasson and Mattsson, 2006; Small and Verhoef, 2007). For example, a de minimis exemption to exclude small emitters (small fuel users) could be considered. To make fuel tax a more effective policy instrument for reducing fuel consumption and CO_2 emissions, it is necessary to undertake further research to analyze and design a tax scheme that would address the uneven effects of fuel taxation and help reduce fuel consumption and CO_2 emissions more effectively. The combined effects of an emissions trading system and fuel tax should also be analyzed in future research.

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Figure 1: Fuel consumption per mile flown by US carriers

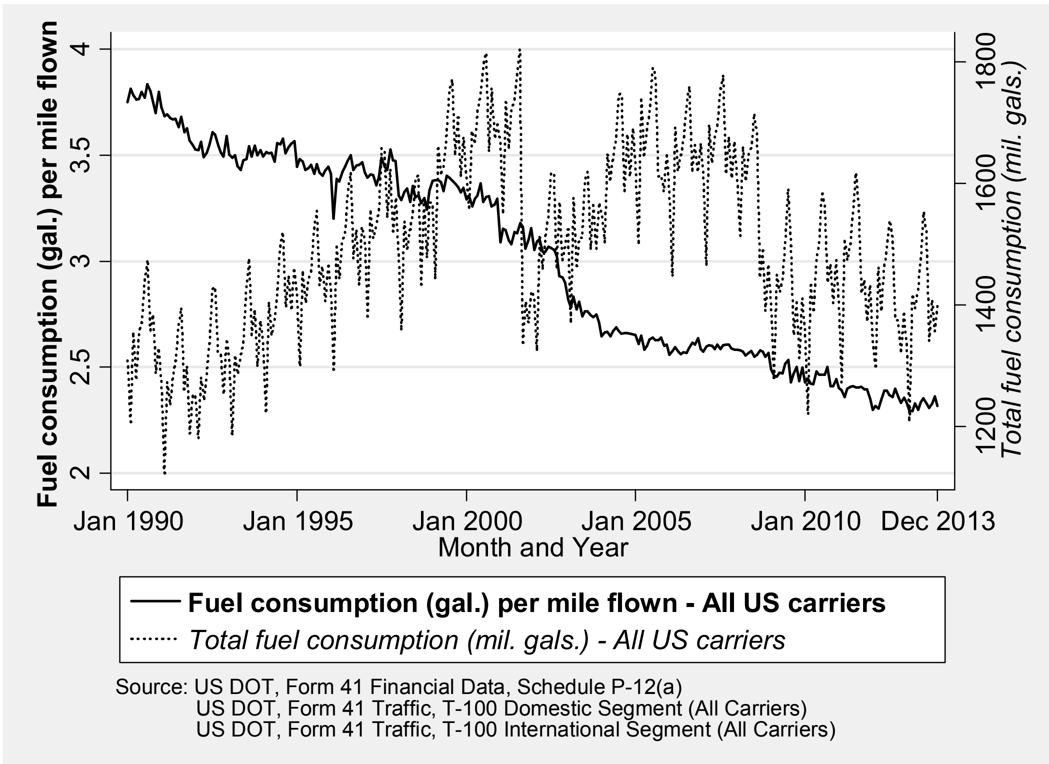

Figure 2: Monthly total miles flown by US carriers

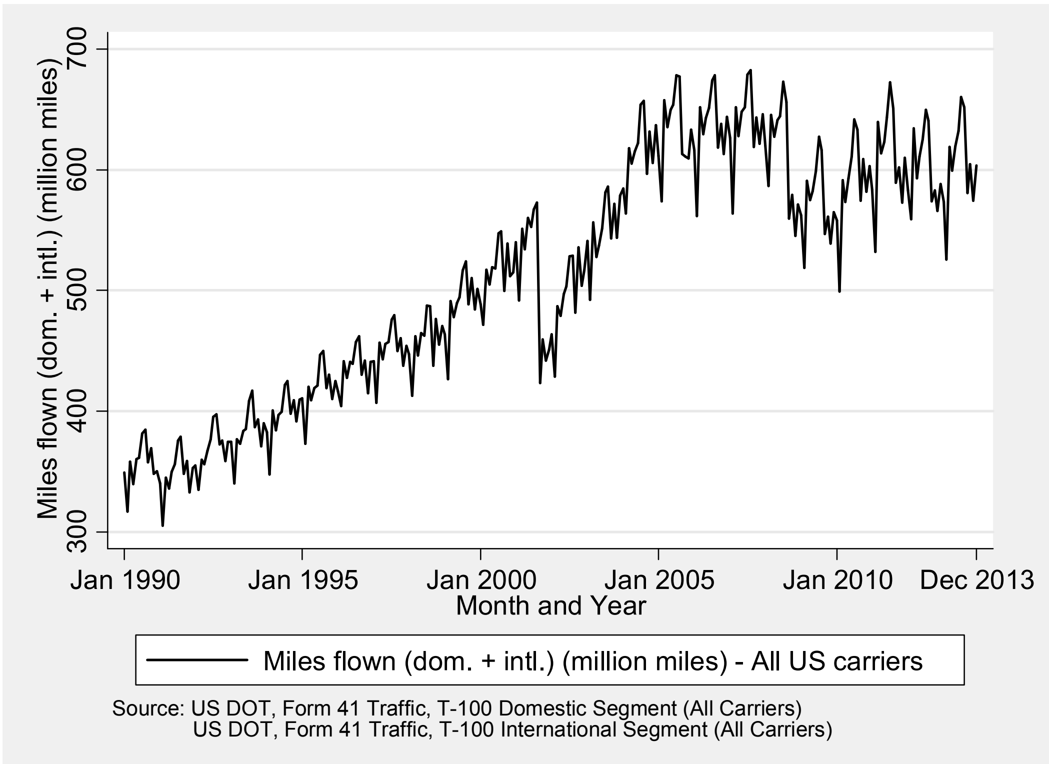

Figure 3: Annual total CO2 emissions in the US

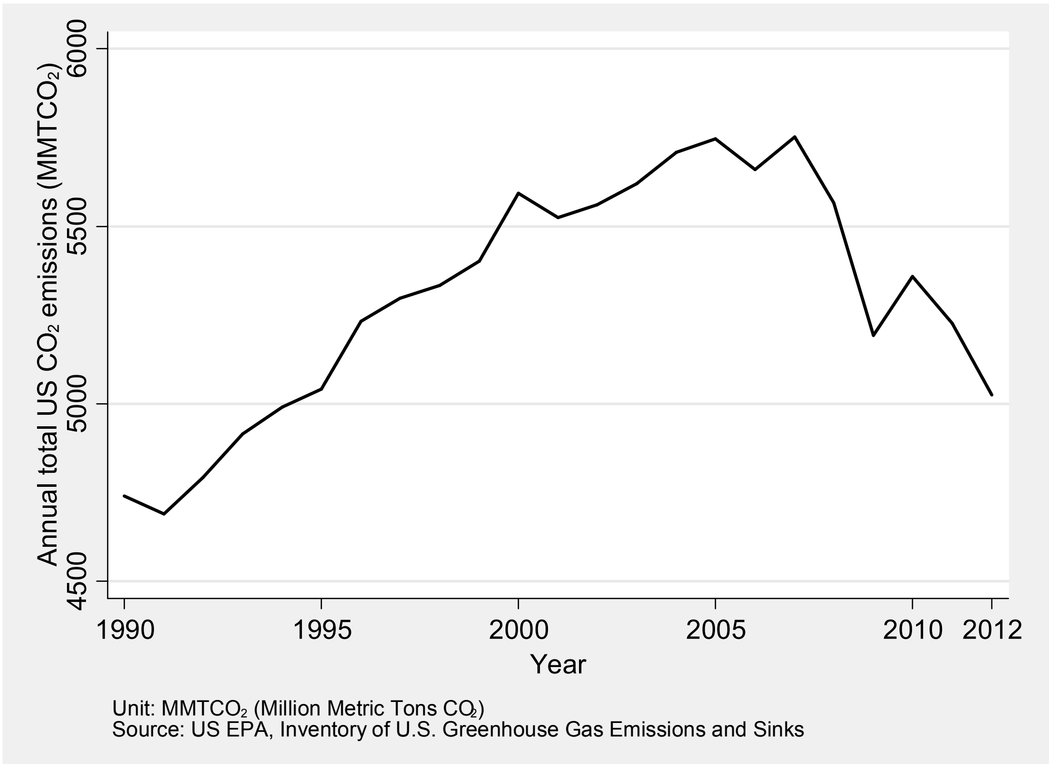

Figure 4: Annual CO2 emissions from commercial flights in the US

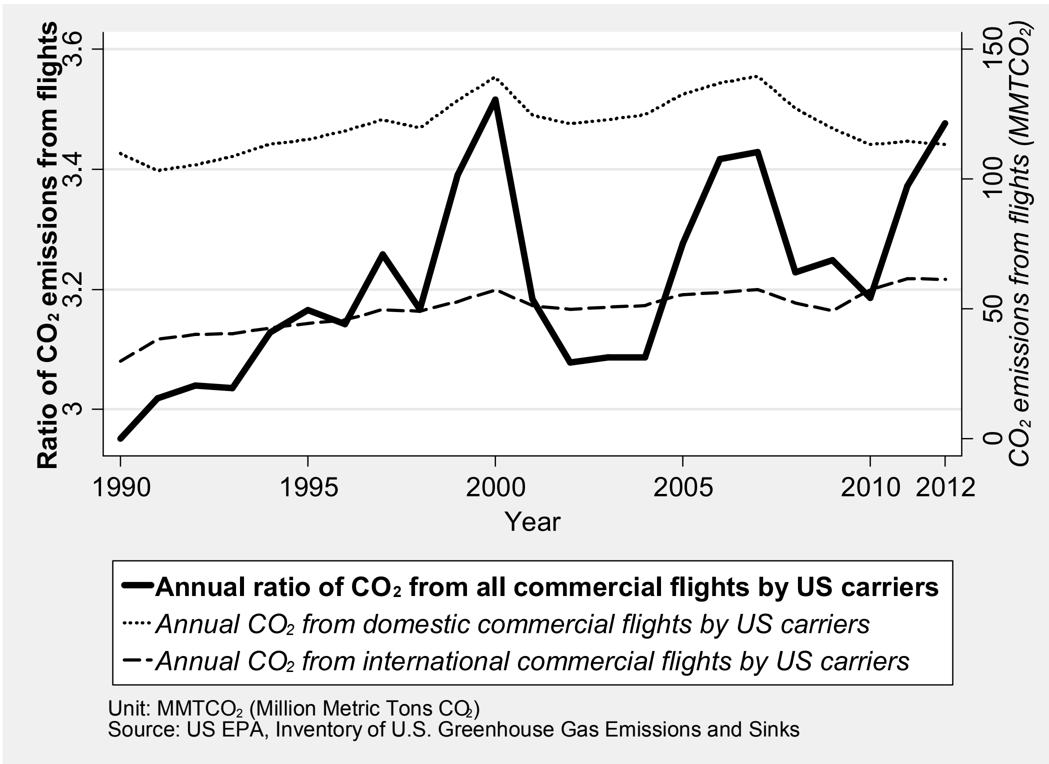

Table 1: Tax rates on aviation fuel in the US since 1994

Year	Quarter	Commercial use of aviation fuel ($)
1994	1 through 4	0.001
1995	1 through 3	0.001
	4	0.044
1996	1 through 4	0.043
1997	1 through 3	0.043
	4	0.044
1998	1 through 4	0.044
1999	1 through 4	0.044
2000	1 through 4	0.044
2001	1 through 4	0.044
2002	1 through 4	0.044
2003	1 through 4	0.044
2004	1 through 4	0.044
2005	1 through 4	0.044
2006	1 through 4	0.044
2007	1 through 4	0.044
2008	1 through 4	0.044
2009	1 through 4	0.044
2010	1 through 4	0.044
2011	1 through 4	0.044
2012	1 through 4	0.044
2013	1 through 4	0.044

Source: US IRS, Publication 510

Table 2: Descriptive statistics

Panel A: data set for the static model (Period: 1995-2013)	Mean	Std. Dev.	Min	Max
Carrier's annual fuel cost per gallon (domestic and international) deflated by CPI (logged) (t-1)	-0.243	0.498	-1.720	1.588
September 11 attacks dummy: 1 for 2001 and 2002	0.103	0.304	0	1
Carrier's annual total miles flown on domestic and international flights (logged) (t-1)	16.728	2.297	5.984	20.858
All carriers' annual average miles flown (domestic and international) per gallon (logged) (t-1)	-0.968	0.0796	-1.188	-0.886
US annual average of monthly national unemployment rate (seasonally adjusted) (%)	5.955	1.718	3.967	9.625
US annual average of monthly per capita personal income (logged)	10.411	0.0936	10.210	10.523
Observations		1024		

Panel B: data set for the distributed lag model (Period: 1997-2013)	Mean	Std. Dev.	Min	Max
Carrier's annual fuel cost per gallon (domestic and international) deflated by CPI (logged) (t-1)	-0.222	0.471	-1.720	1.204
Carrier's annual fuel cost per gallon (domestic and international) deflated by CPI (logged) (t-2)	-0.271	0.473	-1.181	1.547
Carrier's annual fuel cost per gallon (domestic and international) deflated by CPI (logged) (t-3)	-0.315	0.481	-1.181	1.588
September 11 attacks dummy: 1 for 2001 and 2002	0.112	0.316	0	1
Carrier's annual total miles flown on domestic and international flights (logged) (t-1)	16.939	2.301	5.984	20.858
All carriers' annual average miles flown (domestic and international) per gallon (logged) (t-1)	-0.969	0.0830	-1.188	-0.886
US annual average of monthly national unemployment rate (seasonally adjusted) (%)	6.0800	1.826	3.967	9.625
US annual average of monthly per capita personal income (logged)	10.433	0.0743	10.254	10.523
Observations		821		

Carrier and year dummies are omitted for brevity.

Table 3: Estimation results from OLS

Dependent variable: Each carrier's annual total jet fuel consumption (domestic and international; gallons; logged)

	Static model		Distributed lag model	
	(1) OLS: 1995-2013	(2) OLS: 1995-2013	(3) OLS: 1997-2013	(4) OLS: 1997-2013
Carrier's annual fuel cost per gallon (domestic and international) deflated by CPI (logged) (t-1)	-0.431*	-0.414**	-0.293	-0.247
	(0.189)	(0.131)	(0.240)	(0.158)
Carrier's annual fuel cost per gallon (domestic and international) deflated by CPI (logged) (t-2)			-0.103	-0.0343
			(0.133)	(0.100)
Carrier's annual fuel cost per gallon (domestic and international) deflated by CPI (logged) (t-3)			0.0948	-0.0472
			(0.155)	(0.145)
September 11 attacks dummy: 1 for 2001 and 2002	1.138	-0.151	1.986	-0.0588
	(1.685)	(0.163)	(1.509)	(0.155)
Carrier's annual total miles flown on domestic and international flights (logged) (t-1)	0.278*	0.287*	0.259*	0.274*
	(0.124)	(0.126)	(0.129)	(0.135)
All carriers' annual average miles flown (domestic and international) per gallon (logged) (t-1)	4.363	-0.881	9.542	-0.711
	(5.938)	(0.775)	(7.012)	(0.747)
US annual average of monthly national unemployment rate (seasonally adjusted) (%)	0.0157	-0.0347	0.0123	-0.0339
	(0.0354)	(0.0265)	(0.0409)	(0.0338)
US annual average of monthly per capita personal income (logged)		2.084*		1.385
		(0.822)		(1.083)
Carrier fixed effects	Yes	Yes	Yes	Yes
Year fixed effects	Yes	No	Yes	No
Observations	1024	1024	821	821
Adjusted R^2	0.866	0.864	0.869	0.865

Standard errors in parentheses are clustered by carrier. The data set is an unbalanced panel. Unit of observation is carrier by year. Carrier and year dummies are omitted for brevity. The federal fuel tax is included only in fuel cost for domestic flights. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 4: Long-run price elasticity of fuel consumption estimated by OLS

	(1) OLS: 1997-2013
Carrier's annual fuel cost per gallon (domestic and international) deflated by CPI (logged) (t-1)	-0.329
	(0.198)
Controls	Yes
Carrier fixed effects	Yes
Year fixed effects	No
Observations	821
Adjusted R^2	0.865

Standard errors in parentheses are clustered by carrier. The data set is an unbalanced panel. Unit of observation is carrier by year. Carrier and year dummies are omitted for brevity. The federal fuel tax is included only in fuel cost for domestic flights. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 5: Estimation results from simultaneous quantile regression (static model)
Dependent variable: Each carrier's annual total jet fuel consumption (domestic and international; gallons; logged)

Panel A	(1) Q=0.1	(2) Q=0.2	(3) Q=0.3	(4) Q=0.4	(5) Q=0.5	(6) Q=0.6	(7) Q=0.7	(8) Q=0.8	(9) Q=0.9
Carrier's annual fuel cost per gallon (domestic and international) deflated by CPI (logged) (t-1)	-0.499*	-0.605**	-0.538**	-0.349*	-0.355**	-0.290*	-0.242*	-0.196	-0.0978
	(0.211)	(0.197)	(0.179)	(0.145)	(0.125)	(0.117)	(0.113)	(0.110)	(0.114)
September 11 attacks dummy: 1 for 2001 and 2002	5.990	-0.941	0.0388	-0.604	-0.384	-0.431	0.00438	0.0439	-0.369
	(5.441)	(4.582)	(3.279)	(2.236)	(1.697)	(1.425)	(1.110)	(1.115)	(1.124)
Carrier's annual total miles flown on domestic and international flights (logged) (t-1)	0.490***	0.474***	0.270**	0.258***	0.242***	0.199***	0.156**	0.125*	0.0666
	(0.0921)	(0.103)	(0.0948)	(0.0683)	(0.0560)	(0.0554)	(0.0527)	(0.0502)	(0.0475)
All carriers' annual average miles flown (domestic and international) per gallon (logged) (t-1)	21.22	-3.722	-0.251	-1.842	-1.159	-1.325	0.271	0.547	-0.888
	(19.46)	(16.36)	(11.70)	(7.966)	(6.050)	(5.073)	(3.959)	(3.966)	(4.000)
US annual average national unemployment rate (seasonally adjusted) (%)	0.0383	0.0562	0.0603*	0.0110	0.00912	0.00870	0.0115	0.00475	-0.00351
	(0.0342)	(0.0318)	(0.0293)	(0.0243)	(0.0207)	(0.0199)	(0.0196)	(0.0188)	(0.0184)
Carrier fixed effects					Yes				
Year fixed effects					Yes				
Observations					1024				
Pseudo R^2	0.752	0.743	0.747	0.757	0.764	0.778	0.799	0.819	0.834

Table 5 (continued): Estimation results from simultaneous quantile regression (static model)
Dependent variable: Each carrier's annual total jet fuel consumption (domestic and international; gallons; logged)

Panel B	(1) Q=0.1	(2) Q=0.2	(3) Q=0.3	(4) Q=0.4	(5) Q=0.5	(6) Q=0.6	(7) Q=0.7	(8) Q=0.8	(9) Q=0.9
Carrier's annual fuel cost per gallon (domestic and international) deflated by CPI (logged) (t-1)	-0.350**	-0.318***	-0.267***	-0.220**	-0.218***	-0.192***	-0.207***	-0.209***	-0.166**
	(0.115)	(0.0911)	(0.0775)	(0.0665)	(0.0596)	(0.0539)	(0.0515)	(0.0575)	(0.0633)
September 11 attacks dummy: 1 for 2001 and 2002	0.0515	-0.00510	-0.0272	-0.0699	-0.0644	-0.0420	-0.0370	0.0330	0.00745
	(0.0700)	(0.0719)	(0.0800)	(0.0801)	(0.0813)	(0.0791)	(0.0767)	(0.0821)	(0.0884)
Carrier's annual total miles flown on domestic and international flights (logged) (t-1)	0.464***	0.466***	0.333***	0.275***	0.247***	0.189**	0.140*	0.0895	0.0383
	(0.0923)	(0.0904)	(0.0869)	(0.0669)	(0.0598)	(0.0625)	(0.0598)	(0.0529)	(0.0456)
All carriers' annual average miles flown (domestic and international) per gallon (logged) (t-1)	0.121	-0.0414	-0.228	-0.425	-0.346	-0.350	-0.311	0.124	0.158
	(0.321)	(0.328)	(0.346)	(0.346)	(0.334)	(0.318)	(0.307)	(0.331)	(0.369)
US annual average of monthly national unemployment rate (seasonally adjusted) (%)	-0.0192	-0.00884	-0.0116	-0.0105	-0.0146	-0.0106	-0.00591	-0.00861	-0.0131
	(0.0165)	(0.0120)	(0.00938)	(0.00794)	(0.00747)	(0.00705)	(0.00710)	(0.00752)	(0.00793)
US annual average of monthly per capita personal income (logged)	2.294***	1.767***	1.850***	1.812***	1.970***	1.962***	2.126***	2.262***	2.228***
	(0.618)	(0.452)	(0.390)	(0.369)	(0.351)	(0.319)	(0.284)	(0.280)	(0.306)
Carrier fixed effects					Yes				
Year fixed effects					No				
Observations					1024				
Pseudo R^2	0.743	0.738	0.744	0.754	0.761	0.776	0.796	0.814	0.827

Standard errors in parentheses are obtained by 1000 bootstrap replications. The data set is an unbalanced panel. Unit of observation is carrier by year. Carrier and year dummies are omitted for brevity. The federal fuel tax is included only in fuel cost for domestic flights. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 6: Estimation results from simultaneous quantile regression (distributed lag model)
Dependent variable: Each carrier's annual total jet fuel consumption (domestic and international; gallons; logged)

Panel A	(1) Q=0.1	(2) Q=0.2	(3) Q=0.3	(4) Q=0.4	(5) Q=0.5	(6) Q=0.6	(7) Q=0.7	(8) Q=0.8	(9) Q=0.9
Carrier's annual fuel cost per gallon (domestic and international) deflated by CPI (logged) (t-1)	-0.366	-0.475	-0.340	-0.247	-0.110	-0.00436	-0.0797	-0.152	-0.129
	(0.267)	(0.254)	(0.230)	(0.208)	(0.188)	(0.177)	(0.165)	(0.152)	(0.147)
Carrier's annual fuel cost per gallon (domestic and international) deflated by CPI (logged) (t-2)	-0.0619	-0.0233	0.0181	-0.0638	-0.0985	-0.0489	-0.0525	-0.0600	-0.0241
	(0.255)	(0.211)	(0.174)	(0.155)	(0.150)	(0.151)	(0.149)	(0.143)	(0.137)
Carrier's annual fuel cost per gallon (domestic and international) deflated by CPI (logged) (t-3)	0.156	0.129	0.0159	0.0590	0.0786	0.0380	0.113	0.191	0.0968
	(0.207)	(0.165)	(0.126)	(0.110)	(0.103)	(0.106)	(0.111)	(0.105)	(0.0938)
September 11 attacks dummy: 1 for 2001 and 2002	11.41	3.929	2.954	1.212	-0.193	0.127	0.337	0.242	-0.238
	(7.852)	(7.221)	(6.047)	(4.970)	(4.058)	(3.391)	(3.002)	(2.366)	(2.362)
Carrier's annual total miles flown on domestic and international flights (logged) (t-1)	0.513***	0.437***	0.299**	0.240*	0.212**	0.180*	0.167*	0.0954	0.0402
	(0.118)	(0.127)	(0.115)	(0.0943)	(0.0797)	(0.0710)	(0.0667)	(0.0599)	(0.0494)
All carriers' annual average miles flown (domestic and international) per gallon (logged) (t-1)	40.36	13.56	10.23	4.403	-0.581	0.721	1.284	1.104	-0.611
	(28.03)	(25.78)	(21.58)	(17.74)	(14.49)	(12.11)	(10.71)	(8.428)	(8.394)
US annual average of monthly national unemployment rate (seasonally adjusted) (%)	0.0254	0.0406	0.0387	0.0124	0.00239	-0.0132	-0.0134	-0.0154	-0.00706
	(0.0534)	(0.0467)	(0.0411)	(0.0363)	(0.0323)	(0.0285)	(0.0242)	(0.0215)	(0.0215)
Carrier fixed effects					Yes				
Year fixed effects					Yes				
Observations					821				
Pseudo R^2	0.766	0.757	0.763	0.769	0.778	0.791	0.809	0.829	0.840

Table 6 (continued): Estimation results from simultaneous quantile regression (distributed lag model)
Dependent variable: Each carrier's annual total jet fuel consumption (domestic and international; gallons; logged)

Panel B	(1) Q=0.1	(2) Q=0.2	(3) Q=0.3	(4) Q=0.4	(5) Q=0.5	(6) Q=0.6	(7) Q=0.7	(8) Q=0.8	(9) Q=0.9
Carrier's annual fuel cost per gallon (domestic and international) deflated by CPI (logged) (t-1)	-0.186	-0.220*	-0.211**	-0.166*	-0.120	-0.115*	-0.116*	-0.147*	-0.130*
	(0.0962)	(0.0895)	(0.0790)	(0.0680)	(0.0614)	(0.0565)	(0.0557)	(0.0574)	(0.0595)
Carrier's annual fuel cost per gallon (domestic and international) deflated by CPI (logged) (t-2)	-0.151	-0.0459	0.0257	-0.0306	-0.0782	-0.0780	-0.0986	-0.0595	-0.0272
	(0.0911)	(0.0776)	(0.0693)	(0.0644)	(0.0598)	(0.0567)	(0.0584)	(0.0596)	(0.0613)
Carrier's annual fuel cost per gallon (domestic and international) deflated by CPI (logged) (t-3)	-0.00876	-0.0339	-0.0413	0.0225	0.0320	0.0601	0.0712	0.111	0.0873
	(0.103)	(0.0934)	(0.0772)	(0.0694)	(0.0631)	(0.0613)	(0.0657)	(0.0675)	(0.0644)
September 11 attacks dummy: 1 for 2001 and 2002	0.0818	0.0347	-0.0151	-0.0723	-0.000150	-0.00952	-0.00764	0.0648	0.0555
	(0.0585)	(0.0654)	(0.0760)	(0.0808)	(0.0840)	(0.0853)	(0.0835)	(0.0796)	(0.0775)
Carrier's annual total miles flown on domestic and international flights (logged) (t-1)	0.522***	0.482***	0.338**	0.257**	0.213**	0.159*	0.150*	0.0718	0.0449
	(0.102)	(0.110)	(0.105)	(0.0882)	(0.0799)	(0.0755)	(0.0688)	(0.0549)	(0.0440)
All carriers' annual average miles flown (domestic and international) per gallon (logged) (t-1)	0.197	0.0674	-0.214	-0.511	-0.181	-0.262	-0.0814	0.215	0.292
	(0.313)	(0.329)	(0.353)	(0.361)	(0.363)	(0.356)	(0.350)	(0.346)	(0.331)
US annual average of monthly national unemployment rate (seasonally adjusted) (%)	0.00455	-0.00225	-0.0120	-0.0122	-0.0144	-0.0168	-0.0163	-0.0187	-0.0216*
	(0.0215)	(0.0161)	(0.0126)	(0.0106)	(0.00970)	(0.00977)	(0.0102)	(0.00988)	(0.00928)
US annual average of monthly per capita personal income (logged)	2.090***	1.867***	1.696**	1.707***	1.861***	1.774***	1.507***	1.668***	1.330***
	(0.511)	(0.532)	(0.524)	(0.481)	(0.450)	(0.424)	(0.400)	(0.376)	(0.387)
Carrier fixed effects					Yes				
Year fixed effects					No				
Observations					821				
Pseudo R^2	0.757	0.752	0.760	0.767	0.775	0.788	0.805	0.823	0.832

Standard errors in parentheses are obtained by 1000 bootstrap replications. The data set is an unbalanced panel. Unit of observation is carrier by year. Carrier and year dummies are omitted for brevity. The federal fuel tax is included only in fuel cost for domestic flights. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 7: Long-run price elasticity of fuel consumption estimated by simultaneous quantile regression

	(1) Q=0.1	(2) Q=0.2	(3) Q=0.3	(4) Q=0.4	(5) Q=0.5	(6) Q=0.6	(7) Q=0.7	(8) Q=0.8	(9) Q=0
Carrier's annual fuel cost per gallon (domestic and international) deflated by CPI (logged) (t-1)	-0.346**	-0.300*	-0.227*	-0.174	-0.166*	-0.133	-0.143	-0.0958	-0.070
	(0.130)	(0.123)	(0.106)	(0.0907)	(0.0836)	(0.0811)	(0.0783)	(0.0749)	(0.0707
Controls					All				
Carrier fixed effects					Yes				
Year fixed effects					No				
Observations					821				
Pseudo R^2	0.757	0.752	0.760	0.767	0.775	0.788	0.805	0.823	0.832

Standard errors in parentheses are obtained by 1000 bootstrap replications. The data set is an unbalanced panel. Unit of observation is carrier by year. Control variables are omitted for brevity. The federal fuel tax is included only in fuel cost for domestic flights. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 8: Short-run effect of aviation fuel tax on fuel consumption and CO_2 emissions

Panel A						Emission factor for jet fuel (kg CO_2 per gallon)		
						IATA	IPCC	US EPA
						11.924	10.167	9.75
Consumption quantile	Aviation fuel tax ($) (2012)	Increase of tax ($)	Estimated price elasticities	Decrease in fuel consumption (%) (2012)	Decrease in fuel consumption (1000 gallons) (2012)	Reduction in CO_2 emissions ($MMTCO_2$) (2012) (Percentage reduction in CO_2 emissions)		
0.1 or under			-0.350	-2.142	-3881	-0.046 (-0.000970)	-0.039 (-0.000826)	-0.038 (-0.000792)
0.1 - 0.2			-0.318	-2.220	-13515	-0.161 (-0.00338)	-0.137 (-0.00288)	-0.132 (-0.00276)
0.2 - 0.3			-0.267	-1.777	-26171	-0.312 (-0.00654)	-0.266 (-0.00557)	-0.255 (-0.00534)
0.3 - 0.4			-0.220	-1.503	-43053	-0.514 (-0.0108)	-0.438 (-0.00916)	-0.420 (-0.00879)
0.4 - 0.5	0.044	0.1	-0.218	-1.522	-71498	-0.854 (-0.0179)	-0.727 (-0.0152)	-0.697 (-0.0146)
0.5 - 0.6			-0.192	-1.342	-94786	-1.132 (-0.0237)	-0.964 (-0.0202)	-0.924 (-0.0193)
0.6 - 0.7			-0.207	-1.445	-161300	-1.926 (-0.0403)	-1.640 (-0.0343)	-1.573 (-0.0329)
0.7 - 0.8			-0.209	-1.833	-427400	-5.103 (-0.107)	-4.346 (-0.0910)	-4.167 (-0.0872)
0.8 - 0.9			-0.166	-1.185	-782300	-9.339 (-0.196)	-7.954 (-0.167)	-7.627 (-0.160)
Total	-	-	-	-	-1623903	-19.387 (-0.406)	-16.511 (-0.346)	-15.833 (-0.331)

Table 8 (continued): Short-run effect of aviation fuel tax on fuel consumption and CO_2 emissions

Panel B						Emission factor for jet fuel (kg CO_2 per gallon)		
						IATA	IPCC	US EPA
						11.924	10.167	9.75
Consumption quantile	Aviation fuel tax ($) (2012)	Increase of tax ($)	Estimated price elasticities	Decrease in fuel consumption (%) (2012)	Decrease in fuel consumption (1000 gallons) (2012)	Reduction in CO_2 emissions ($MMTCO_2$) (2012) (Percentage reduction in CO_2 emissions)		
0.1 or under			-0.350	-0.921	-1669	-0.0199 (-0.000417)	-0.0170 (-0.000355)	-0.0163 (-0.000341)
0.1 - 0.2			-0.318	-0.955	-5811	-0.0694 (-0.00145)	-0.0591 (-0.00124)	-0.0567 (-0.00119)
0.2 - 0.3			-0.267	-0.764	-11253	-0.134 (-0.00281)	-0.114 (-0.00240)	-0.110 (-0.00230)
0.3 - 0.4			-0.220	-0.646	-18513	-0.221 (-0.00463)	-0.188 (-0.00394)	-0.180 (-0.00378)
0.4 - 0.5	0.044	0.043	-0.218	-0.654	-30744	-0.367 (-0.00768)	-0.313 (-0.00654)	-0.300 (-0.00628)
0.5 - 0.6			-0.192	-0.577	-40758	-0.487 (-0.0102)	-0.414 (-0.00868)	-0.397 (-0.00832)
0.6 - 0.7			-0.207	-0.621	-69345	-0.828 (-0.0173)	-0.705 (-0.0148)	-0.676 (-0.0142)
0.7 - 0.8			-0.209	-0.788	-183800	-2.194 (-0.0459)	-1.869 (-0.0391)	-1.792 (-0.0375)
0.8 - 0.9			-0.166	-0.510	-336400	-4.016 (-0.0841)	-3.420 (-0.0716)	-3.280 (-0.0687)
Total	-	-	-	-	-698293	-8.337 (-0.175)	-7.100 (-0.149)	-6.808 (-0.143)

Source: IATA, Carbon Offset Program - Frequently Asked Questions, Version9, 17 January 2014 (IATA, 2014), p.8.
IPCC, 2006 IPCC Guidelines for National Greenhouse Gas Inventories (corrected as of June 2014), Volume 2 – Energy, Chapter 2 (Stationary Combustion), p.16; Chapter 3 (Mobile Combustion), p.64.
US EPA, Emission Factors for Greenhouse Gas Inventories, Last Modified: 4 April 2014, Tables 1 and 2.

Table 9: Long-run effect of aviation fuel tax on fuel consumption and CO_2 emissions

Panel A

Consumption quantile	Aviation fuel tax ($) (2012)	Increase of tax ($)	Estimated price elasticities	Decrease in fuel consumption (%) (2012)	Decrease in fuel consumption (1000 gallons) (2012)	Reduction in CO_2 emissions ($MMTCO_2$) (2012) (Percentage reduction in CO_2 emissions): IATA 11.924	IPCC 10.167	US EPA 9.75
0.1 or under	0.044	0.1	-0.346	-2.113	-3828	-0.0457 (-0.000957)	-0.0389 (-0.000815)	-0.037 (-0.000781)
0.1 - 0.2			-0.300	-2.095	-12752	-0.152 (-0.00319)	-0.130 (-0.00271)	-0.124 (-0.00260)
0.2 - 0.3			-0.227	-1.506	-22177	-0.265 (-0.00554)	-0.225 (-0.00472)	-0.216 (-0.00453)
0.4 - 0.5			-0.166	-1.160	-54480	-0.650 (-0.0136)	-0.554 (-0.0116)	-0.531 (-0.0111)
Total	-	-	-	-	-93237	-1.113 (-0.0233)	-0.948 (-0.0198)	-0.909 (-0.0190)

Panel B

Consumption quantile	Aviation fuel tax ($) (2012)	Increase of tax ($)	Estimated price elasticities	Decrease in fuel consumption (%) (2012)	Decrease in fuel consumption (1000 gallons) (2012)	Reduction in CO_2 emissions ($MMTCO_2$) (2012) (Percentage reduction in CO_2 emissions): IATA 11.924	IPCC 10.167	US EPA 9.75
0.1 or under	0.044	0.043	-0.346	-0.909	-1646	-0.0197 (-0.000411)	-0.0167 (-0.000350)	-0.0161 (-0.000336)
0.1 - 0.2			-0.300	-0.901	-5483	-0.0655 (-0.00137)	-0.0557 (-0.00117)	-0.0535 (-0.00112)
0.2 - 0.3			-0.227	-0.647	-9536	-0.114 (-0.00238)	-0.0970 (-0.00203)	-0.0930 (-0.00195)
0.4 - 0.5			-0.166	-0.499	-23426	-0.280 (-0.00586)	-0.238 (-0.00499)	-0.228 (-0.00478)
Total	-	-	-	-	-40092	-0.479 (-0.0100)	-0.408 (-0.00853)	-0.391 (-0.00818)

Emission factor for jet fuel (kg CO_2 per gallon): IATA 11.924; IPCC 10.167; US EPA 9.75.

Source: IATA, Carbon Offset Program - Frequently Asked Questions, Version9, 17 January 2014 (IATA, 2014), p.8.
IPCC, 2006 IPCC Guidelines for National Greenhouse Gas Inventories (corrected as of June 2014), Volume 2 – Energy, Chapter 2 (Stationary Combustion), p.16; Chapter 3 (Mobile Combustion), p.64.
US EPA, Emission Factors for Greenhouse Gas Inventories, Last Modified: 4 April 2014, Tables 1 and 2.

Table 10: Effect of a change of aviation fuel tax on the change of jet fuel price
Dependent variable: Each carrier's annual jet fuel cost per gallon with fuel tax ($) deflated by CPI (logged)

	(1) Model 1	(2) Model 2
Tax Rates on Aviation Jet Fuel	0.0406***	0.0466***
($) deflated by CPI (logged)	(0.00947)	(0.00517)
Controls	Excluding the income variable	All
Carrier fixed effects	Yes	Yes
Year fixed effects	Yes	No
Adjusted R^2 / Pseudo R^2	0.856	0.563
Observations	297	

Standard errors in parentheses are clustered by carrier. Carrier and year fixed effects are omitted for brevity. Controls are as follows: Carrier's annual total miles flown on domestic flights (logged) (t-1); All carriers' annual average miles flown (domestic) per gallon (logged) (t-1); US annual average national unemployment rate (seasonally adjusted) (%); and annual average of US monthly per capita personal income (logged). * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 11: Estimated average annual pass-through rate (%) of aviation fuel tax to aviation fuel price

	(1) Model 1	(2) Model 2
1996	48.1	55.2
1997	45.3	52.0
1998	35.1	40.3
1999	38.6	44.3
2000	54.3	62.3

Appendix A: Data sources

Aviation Fuel Consumption & Aviation Fuel Price

US Department of Transportation, Air Carrier Financial Reports (Form 41 Financial Data), Schedule P-12(a)
http://www.transtats.bts.gov/Fields.asp?Table_ID=294

Aviation Fuel Tax

US Department of the Treasury, Internal Revenue Service, Publication 510 (Prior Year Forms and Publications)
http://apps.irs.gov/app/picklist/list/priorFormPublication.html
http://www.irs.gov/Forms-&-Pubs/Prior-Year-Forms

Market Segment Specialization Program - Aviation Tax
US Department of the Treasury, Internal Revenue Service
Training 3123-004 (2-99), TPDS No. 83026E
http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.198.4714&rep=rep1&type=pdf

Carbon emissions

US EPA - National Greenhouse Gas Emissions Data - Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2012 (April 2014)
http://www.epa.gov/climatechange/ghgemissions/usinventoryreport.html

Emission factors

IATA, Carbon Offset Program - Frequently Asked Questions, Version 9, 17 January 2014
http://www.iata.org/whatwedo/environment/Documents/carbon-offset-program-faq-airline-participants.pdf

IPCC, 2006 IPCC Guidelines for National Greenhouse Gas Inventories (corrected as of June 2014), Volume 2 – Energy
http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html
http://www.ipcc-nggip.iges.or.jp/public/2006gl/vol2.html

US EPA - Emission Factors for Greenhouse Gas Inventories, Last Modified: 4 April 2014
http://www.epa.gov/climateleadership/inventory/ghg-emissions.html
http://www.epa.gov/climateleadership/documents/emission-factors.pdf
http://www.epa.gov/climateleadership/documents/emission-factors.xls

Monthly per capita income

US Department of Commerce, Bureau of Economic Analysis, GDP and the National Income and Product Account (NIPA) Historical Tables, Table 2.6. Personal Income and Its Disposition, Monthly [Billions of dollars; months seasonally adjusted at annual rates]; Monthly data from 1969 To 2014; Chained (2009) dollars http://www.bea.gov//national/nipaweb/DownSS2.asp

Monthly population

US Department of Commerce, Bureau of the Census, National Intercensal Estimates (1990-2000 & 2000-2010 & 2010s)
http://www.census.gov/popest/data/intercensal/national/index.html
http://www.census.gov/popest/data/intercensal/national/nat2010.html
http://www.census.gov/popest/data/national/asrh/2013/2013-nat-res.html;
Regional Economic Accounts
http://www.bea.gov/regional/index.htm

Monthly unemployment rate (seasonally adjusted)

US Department of Labor, Bureau of Labor Statistics, Labor Force Statistics including the National Unemployment Rate (Current Population Survey - CPS); Labor Force Statistics from the Current Population Survey; Series Id: LNS14000000; Seasonally Adjusted; Series title: (Seas) Unemployment Rate; Labor force status; Unemployment rate; Type of data: Percent or rate; Age: 16 years and over; Years: 1948 to 2014
http://www.bls.gov/data/
http://www.bls.gov/cps/
http://data.bls.gov/pdq/SurveyOutputServlet

Appendix B: List of air carriers appeared in the data set, 1995 - 2013

Serial Number	Carrier code	Carrier name	Years covered by the data set
1	16	PSA Airlines Inc.	2005-2010
2	0JQ	Vision Airlines	2012
3	0WQ	Avjet Corporation	2011-2013
4	5V	Tatonduk Outfitters Limited d/b/a Tatonduk Flying Service	2000-2003
	5V	Tatonduk Outfitters Limited d/b/a Everts Air Alaska and Everts Air Cargo	2005-2007, 2010-2011, 2013
5	5X	United Parcel Service	1995-2013
6	5Y	Atlas Air Inc.	1996-2013
7	8C	Air Transport International	2000-2013
8	9E	Pinnacle Airlines Inc.	2005-2006
9	9L	Colgan Air	2009-2012
10	9S	Southern Air Inc.	2004-2007
11	AA	American Airlines Inc.	1995-2013
12	ABX	Airborne Express Inc.	2003-2005
	ABX	ABX Air, Inc.	2006-2009, 2011-2013
13	AJQ	Aerodynamics Inc.	2004-2011
14	AS	Alaska Airlines Inc.	1995-2013
15	AX	Trans States Airlines	1995-2007
16	B6	JetBlue Airways	2001-2013
17	BF	Markair Inc.	1995
18	BFQ	Buffalo Airways Inc.	1996
19	CDQ	American International Airways Inc.	1995-1998
	CDQ	Kitty Hawk International	1999-2000
20	CO	Continental Air Lines Inc.	1995-2011
21	CP	Compass Airlines	2008-2010
22	DH	Atlantic Coast Airlines	2004
	DH	Independence Air	2005
23	DL	Delta Air Lines Inc.	1995-2013
24	E0	EOS Airlines, Inc.	2008
25	E9	Boston-Maine Airways	2007-2008
26	ER	DHL Airways	1995-2003
	ER	Astar Air Cargo Inc.	2004-2007, 2009
	ER	Astar USA, LLC	2011-2012
27	EV	Atlantic Southeast Airlines	1995-2011
	EV	ExpressJet Airlines Inc.	1996-2001, 2003-2013
28	EZ	Evergreen International Inc.	1995-2007, 2009
29	F2	Omega Air Holdings d/b/a Focus Air	2008
30	F8	Freedom Airlines d/b/a HP Expr	2004
31	F9	Frontier Airlines Inc.	1995-2013
32	FCQ	Falcon Air Express	2002-2006
33	FDQ	Great American Airways	1997
34	FE	Primaris Airlines Inc.	2005
35	FF	Tower Air Inc.	1995-2000
36	FL	AirTran Airways Corporation	1998-2012
37	FNQ	Fine Airlines Inc.	1998-2000
38	FX	Federal Express Corporation	1995-1997, 1999-2013
39	G4	Allegiant Air	2005-2013
40	G7	GoJet Airlines, LLC d/b/a United Express	2006-2012

Serial Number	Carrier code	Carrier name	Years covered by the data set
41	GFQ	Gulf And Caribbean Cargo	2008-2009, 2012-2013
42	GL	Miami Air International	1995-2013
43	GR	Gemini Air Cargo Airways	1997-2008
44	HA	Hawaiian Airlines Inc.	1995-2013
45	HCQ	Av Atlantic	1997
46	HP	America West Airlines Inc.	1995-2007
47	HQ (1)	Business Express	1995-1996
48	J7	Valujet Airlines Inc.	1996-1998
49	JI (1)	Midway Airlines Inc.	1997-1999
50	JKQ	Express One International Inc.	1995-2001
51	JW	Arrow Air Inc.	1995-2004, 2007, 2009-2010
52	JX	Southeast Airlines	2004
53	KAQ	Kalitta Air LLC	2004-2013
54	KH	Aloha Air Cargo	2010-2013
55	KLQ	Kalitta Charters II	2013
56	KP	Kiwi International	1995-1999
57	KR	Kitty Hawk Aircargo	1996-2007
58	KW	Carnival Air Lines Inc.	1995-1998
59	L2	Lynden Air Cargo Airlines	2000-2013
60	L3	Lynx Aviation d/b/a Frontier Airlines	2010-2011
61	M6	Amerijet International	2001-2002, 2004-2013
62	MG	MGM Grand Air Inc.	1995-1996
	MG	Champion Air	1997-2008
63	MQ	Simmons Airlines	1995-1998
	MQ	American Eagle Airlines Inc.	1999-2011
64	N7	National Airlines	2000-2002
65	NA	North American Airlines	1995, 2000-2013
66	NC	Northern Air Cargo Inc.	2003-2013
67	NJ	Vanguard Airlines Inc.	1998-2002
68	NK	Spirit Air Lines	1996-2013
69	NW	Northwest Airlines Inc.	1995-2009
70	OH	Comair Inc.	2003-2012
71	OO	SkyWest Airlines Inc.	2004-2013
72	OW	Executive Airlines	1995-2011
73	PA (2)	Pan American World Airways	1997-1998
74	PCQ	Pace Airlines	2004-2009
75	PN	Pan American Airways Corp.	2003-2004
76	PO	Polar Air Cargo Airways	1995-2013
77	PRQ	Florida West Airlines Inc.	1999-2010
78	QQ	Reno Air Inc.	1995-1999
79	QX	Horizon Air	1995-2010
80	RD	Ryan International Airlines	1999-2010
81	RIQ	Rich International Airways	1995-1996
82	RLQ	Reliant Airlines	2002
83	RP	Chautauqua Airlines Inc.	2013
84	S5	Shuttle America Corp.	2006-2013
85	SAQ	Southern Air Transport Inc.	1995-1997
86	SLQ	Sky King Inc.	2012-2013
87	SPQ	Sun Pacific International	1999
88	SX	Skybus Airlines, Inc.	2008

Serial Number	Carrier code	Carrier name	Years covered by the data set
89	SY	Sun Country Airlines	1995-2004
	SY	Sun Country Airlines d/b/a MN Airlines	2005-2013
90	T9	TransMeridian Airlines	1999-2005
91	TB (1)	USAir Shuttle	1996
92	TCQ	Trans Continental Airlines	2000
	TCQ	Express.Net Airlines	2002-2006
93	TNQ	Emery Worldwide Airlines	1995-2001
94	TW	Trans World Airways LLC	2001
	TW	Trans World Airlines Inc.	1995-2000
95	TZ	American Trans Air Inc.	1995-2002
	TZ	ATA Airlines d/b/a ATA	2003-2008
96	U2	UFS Inc.	1995-2000
97	U5	USA 3000 Airlines	2003-2012
98	U7	USA Jet Airlines Inc.	1998-2013
99	UA	United Air Lines Inc.	1995-2013
100	US	USAir	1995-1996
	US	US Airways Inc.	1997-2013
101	VX	Virgin America	2008-2013
102	W7	Western Pacific Airlines	1996-1998
103	WE	Centurion Cargo Inc.	2007, 2009
104	WN	Southwest Airlines Co.	1995-2013
105	WO	World Airways Inc.	1996, 2000-2013
106	WP	Island Air Hawaii	2013
107	X9	Omni Air Express	2000-2013
108	XJ	Mesaba Airlines	1998-2008, 2011
109	XP	Casino Express	2002-2013
110	YV	Mesa Airlines Inc.	1996-1997, 2004-2013
111	YX	Republic Airlines	2006-2013
112	YX (1)	Midwest Express Airlines	1996-2002
	YX (1)	Midwest Airline, Inc.	2003-2009
113	ZKQ	Zantop International	2002-2003
114	ZW	Air Wisconsin Airlines Corp	1995-2013

- We examine the effect of aviation fuel tax on fuel consumption and CO_2 emissions.
- The data is an unbalanced panel data of US carriers from 1995 to 2013.
- We use a simultaneous quantile regression method.
- The long-run fuel price elasticity varies depending on consumption quantiles.
- A tax increase has a larger impact on smaller carriers than on larger carriers.

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Figure 1_Fuel consumption per mile flown by US carriers.eps
Figure 2_Monthly total miles flown by US carriers.eps
Figure 3_Annual total CO2 emissions in the US.eps
Figure 4_Annual CO2 emissions from commercial flights in the US.eps

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The impact of aviation fuel tax on fuel consumption and carbon emissions: The case of the US airline industry

Fukui, H.

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